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Seismic Design Considerations for Mass Transit Facilities

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Seismic Design Considerations for Mass Transit Facilities

Final Report
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EXECUTIVE SUMMARY

Throughout history, earthquakes have been one of the most severe forms of national disaster, taking high tolls on life and property. Their unpredictability and violence makes it particularly difficult to anticipate and prepare for them.

The federal government has long been concerned with seismic safety, as evidenced by the Earthquake Hazards Reduction Act established by Congress in 1977. The National Earthquake Hazards Reduction Program (NEHRP) was established in response to this legislation on June 22, 1978. Further, Presidential Executive Order 12699, signed January 5, 1990, requires that all new federally sponsored buildings have seismic design and construction standards incorporated. Under the Executive Order, federal agencies are given the responsibility for developing and implementing their own mission-appropriate and cost-effective regulations governing seismic safety. To support the implementation of this order, the Office of the Secretary, DOT, put into regulation on July 14, 1993 49 CFR Part 41 in response to this federal requirement.

The U.S. Department of Transportation (U.S. DOT) is playing an active role in the area of seismic safety. A U.S. DOT Seismic Committee, composed of representatives from each U.S. DOT agency (e.g., Federal Transit Administration (FTA), formerly the Urban Mass Transportation Administration (UMTA) was formed to fully support the federal government's goal on seismic safety issues. In support of FTA's involvement in this committee, the Volpe National Transportation Systems Center (VNTSC), Cambridge, Mass., was asked to provide general seismic design guidelines for select mass transit facilities under FTA's jurisdiction. Specifically, these facilities are underground structures, elevated guideways, and maintenance facilities.

What are earthquakes and why do they represent a risk? Earthquakes are typically generated by a sudden release of energy as the geological blocks which make up the earth's crust move in relation to each other. They are typified by violent and irregular shaking of the ground. The familiar Richter Scale is a measure of their energy, ranging from 1 (detectable only by instruments) to about 8 (mass destruction). The West Coast of the United States is the predominant but not exclusive domain of earthquakes. All states have, in fact, a finite probability of occurrence.

The main risk associated with earthquakes is the potential impact on man-made structures. Those built without proper seismic provisions perform poorly under strong shaking. Recent events throughout the world have shown that high casualties can result from inappropriate forms of construction.

What is the construction industry doing about earthquakes? In general, the awareness of the risk and the provisions made vary greatly by geographic area and by institution. The predominant codes addressing seismic design are the American Association of State Highway and Transportation Officials (AASHTO) Specifications, and the 1991 ICBO Uniform Building Code (UBC). There are also derivatives of these like the 1992 Supplement to the BOCA National Building Code and the 1992 Amendments to the SBCC Standard Building Code adapted for use in particular states or cities.

The codes are each intended for specific applications, and do not provide general guidance. They do not specifically address transit structures and completely ignore underground facilities. Further, it is only in the last few years that an effective approach to earthquake design has evolved, leaving the safety of many older facilities in question.

The transit industry does not have specific codes or guidelines to assist in the seismic design of its facilities. The treatment of earthquake varies greatly throughout the country. Some transit properties make no provisions while others conduct elaborate studies and develop detailed project-specific criteria.

An example of the latter category is the Bay Area Rapid Transit (BART). Because BART was the first of the new generation of rapid transit projects, and because of its location in an active seismic zone, earthquake considerations were given a high priority. The project was very innovative in its approach, and many of its criteria later became valuable references for other systems.

Even now, the design of a new transit facility often leads to the question of what seismic criteria to use. The answer does not usually lie within a single code, but, rather within a combination of several documents, and supplemental project-specific requirements. It is possible, however, to define some general guidelines which may assist the development of detailed seismic criteria for transit structures.

Over the last few years, the combination of academic research, special federal studies, and design development by engineers, has given us a new approach to seismic design. This includes the premise that a structure's ability to deform safely may be more important than actual strength in surviving an earthquake. Structural deformation is often accompanied by damage. Even limited damage, however, may be acceptable provided it is detectable, repairable, and does not result in collapse. The property which gives a structure the ability to deform safely is ductility. This approach is directly applicable in the design of transit facilities. Due to the inherent differences between aboveground and underground structures, however, variations to the approach are necessary.

In developing earthquake criteria for a transit project, the seismic characteristics for the site should be defined. For a large project, especially one in a seismically active area, detailed studies may be necessary. The aim of the studies is to define the anticipated earthquake levels, and to identify potentially dangerous geotechnical phenomena such as fault movements, soil liquefaction, and landslides. Two levels of earthquake are often considered. A Maximum Design Earthquake (MDE) has a high intensity and a low probability of occurrence over the life of the structure. An Operating Design Earthquake (ODE) has a lower intensity but a higher probability that it will occur at least once during the service life of the structure. The underlying concept is that a structure should be able to experience the lower without disruption to service, and should be able to survive the higher with only limited damage.

The design of aerial guideway structures should follow the AASHTO Standard Specifications of 1991. The forces which are calculated from an elastic analysis are reduced by a factor whose value may range from about 2 to 6. The structure is designed for the reduced forces. Larger reduction factors will result in greater seismic displacements and greater damage, and will require higher ductility. In the case of the ODE, the structure should remain unharmed. For the MDE, limited structural damage can be accepted. This should, however, be confined to the tops and bottoms of the piers where it can be more easily detected and repaired.

There are no industry standard guidelines for the design of underground facilities. A recommended approach is to estimate the soil deformations and assume that the structure conforms to these. The internal stresses will be the combined result of the static forces, and the deformations imposed by the soil. As for aerial structures, limited damage can be accepted during an MDE, whereas the ODE is treated more like a conventional load for which there should be no damage.

Maintenance and other miscellaneous facilities which form part of a transit development are usually best covered by the seismic guidelines in the Uniform Building Code. These facilities are typified by low buildings, vehicle storage yards, and a variety of equipment. They are less susceptible to overall collapse than local damage and falling components. Design of these facilities must follow local codes and should concentrate on structural and architectural details which are more resilient and less likely to separate during an earthquake. The support of utilities and mounting of equipment also merits special attention. The failure of gas, power, and water lines can result in safety problems long after the end of the earthquake.

With regard to transit and other facilities, the preparation for earthquakes should go beyond structural provisions, and include safety plans for contingency operations and procedures. These may include turning off utilities, generation of emergency power, and the evacuation of personnel.

Why make provisions? History has shown us that earthquakes often have catastrophic results. The cost of incorporating appropriate considerations at the time of construction is relatively small. In contrast, however, the cost of subsequent repair or replacement is very high, and the suspension of service usually has large community impacts. Further, limited recent experience with retrofit programs, confirms that after-the-fact structural improvements are often of only limited effectiveness.

The transit industry must recognize that earthquakes are a very real threat, and that they can have severe consequences throughout the country. They are not exclusively a West Coast problem. Existing codes do not yet provide comprehensive coverage for all transit applications, but can represent a general guide if used correctly. Our knowledge of earthquakes, and their effects continues to grow, and our design techniques will continue to improve. The immediate concern is that we preserve the safety of transit users and operators, and that we protect the investment in facilities, by including seismic considerations in the development of transit projects.

1. INTRODUCTION

1.1 Background

Of all natural disasters, earthquakes are the most devastating to morale and property. The unpredictable occurrence of strong, damaging earthquakes, coupled with the large geographic areas affected by a single event, gives rise to a staggering sudden economic loss potential. The 1989 Loma Prieta earthquake, near San Francisco, demonstrated that moderate shaking caused more structural damage than expected, even in an area of the country with the most stringent building codes. Additionally, earthquakes are not exclusively a West Coast phenomenon since all portions of the United States have at least some probability of experiencing earthquake-induced ground movement.

The federal government has played a leading role in support of seismic safety programs. A major effort of the federal government stems from the Earthquake Hazards Reduction Act of 1977. The purpose of this act is to provide a comprehensive and integrated national effort, to reduce the losses of life and property from earthquakes, through the establishment and maintenance of an earthquake hazards reduction program. The most recent amendment to the Act was Public Law 101-614 approved in December 1990.

In 1980, the Federal Emergency Management Agency was designated as the lead agency for implementing a National Earthquake Hazards Reduction Program (NEHRP), supported by the U.S. Geological Survey, the National Science Foundation, and the National Institute for Standards and Technology. The NEHRP effort is also supported by several contributing agencies including the U.S. Department of Transportation (USDOT). This program is currently carrying out a 5-year plan for the years 1989 through 1993. The plan includes activities in the following nine areas:

- Leadership
- Earthquake potential and hazard assessment
- Earthquake prediction research
- Earthquake engineering research
- Earthquake planning and mitigation
- Fundamental earthquake studies
- Information systems and dissemination
- Post-earthquake studies
- International cooperation

On January 5, 1990, the President of the United States signed the Executive Order on Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction. Under this directive, all federal government agencies that carry out design and construction must ensure that their buildings follow "appropriate seismic design and construction standards". This provision applies to all building jobs "for which development of detailed plans and specifications is initiated" after January 5, 1990. Federal agencies with assistance or regulatory responsibilities have three years to put implementation regulations in place.

To support the requirements of the Executive Order, the Office of the Secretary, DOT, put into place regulation 49 CFR Part 41 effective July 14, 1993. The rules in this CFR include the design and construction of any of its new buildings for use or ownership, as well as the need for seismic safety recognition in all grant and safety programs affecting federally leased, assisted or regulated buildings. The purpose is to reduce the risk of death or injury to building occupants, improve the capabilities of essential buildings to function during or after an earthquake, and to reduce earthquake losses of public buildings and investments. The rules adopted in this CFR may be further implemented by the DOT Operating Administrations.

USDOT is playing an active role in the area of seismic safety. For example, the Secretary of Transportation has established the overall USDOT goal of reducing seismic risk to personnel and vital activities housed in the buildings and facilities under the Department's jurisdiction, and to improve their functions during and after earthquakes. The USDOT goal fully supports the intent of both the NEHRP and the recent Executive Order on Seismic Safety.

While the major emphasis for seismic safety is in new construction, USDOT is still pursuing long-term objectives of prioritizing courses of action involving mitigation or retrofit programs for buildings and lifelines in high seismic risk areas, and to promote long-term research into methods of increasing seismic resistance for both new and existing structures. A USDOT Seismic Committee was formed in the 1980s and was composed of representatives from each USDOT agency (FTA, FHWA, FAA, etc.). The committee's role is to identify the needs and to implement cost-effective programs of constructing new and upgrading existing mass transit facilities to present seismic requirements. The facilities include highways, bridges, tunnels, airport control towers, terminals, docks, pipelines, rail lines, and other USDOT structures and buildings.

In support of FTA's involvement with the USDOT's Seismic Committee, the Volpe National Transportation Systems Center, Cambridge, Massachusetts, has been requested to develop recommended seismic design considerations for select mass transit facilities. Presently, FTA relies on transit agencies and their consultants to use various building codes and project-specific criteria to address seismic requirements for new construction projects under FTA jurisdiction. In all, there are approximately 1,500 transit systems in both urban and nonurban areas across the nation receiving FTA funds for construction. However, overall guidance on proper incorporation of seismic design requirements for mass transit structures is limited. A 1993 study sponsored by the Office of the Assistant Secretary of Transportation and conducted by the Volpe National Transportation Systems Center addresses the need for assistance in this area and discusses current seismic engineering practices in their final report titled "Seismic Awareness: Transportation Facilities."

1.2 Purpose of Report

Although an immense amount of material has been published on the subject of earthquake science and its engineering applications, the awareness of seismic risk and the approach in dealing with it vary widely throughout the country and the world.

The engineering community generally incorporates seismic considerations on the basis of prevailing codes and guidelines, and the specific policies of the project owner. The available guidelines are not uniform, however, and vary according to geographic location and discipline. In some cases specific guidelines are developed for a particular project, using existing codes and site-specific research as the basis.

Of particular concern here is the application of seismic design to transit structures in the United States. Mass transit represents a large part of local and federally funded public developments, and has a high degree of exposure to the general population. Existing codes do not explicitly address transit structures, although many of their guidelines can be applied. Often the sponsoring agency for a transit development finds very little guidance in seismic design and must invest time and money to formulate an appropriate approach.

The Federal Transit Administration would like to see greater awareness and a more uniform treatment of earthquake considerations in new transit developments. This will be particularly important in view of the recent Presidential Executive Order on seismic safety. This report summarizes the current state of earthquake engineering in this country, and offers general guidance on how to include seismic considerations in transit structures.

2. EARTHQUAKE BACKGROUND

2.1 General

As a result of the immense pressure and temperature within the inner layers of the earth, the relatively thin outer crust is continually subject to movement. Most movements are gradual and can only be detected by careful measurements. Some, however, are the result of sudden releases of elastic energy as the large blocks making up the earth's crust move relative to each other. It is these violent releases that typically cause the phenomenon we call earthquakes.

The location of an earthquake is usually quoted as its epicenter, which is the point on the earth's surface directly above the disturbance. The effect of an earthquake can be very far-reaching as the ground vibrates under the propagation of the generated waves.

The destructive phase of an earthquake may vary in duration from a few seconds to about one minute. It is estimated that throughout the world there are over a million earthquakes every year. The majority are quite weak and many occur in remote unpopulated areas and therefore are noticed only by scientists. It is estimated that a major earthquake (magnitude 7 or greater on the Richter Scale) occurs about once every week.

The size of an earthquake can be described in terms of the impact it has on the developed environment of the area (people and structures), a semi-subjective measure, or it can be classified according to the quantitative measure of the energy released. Both methods have their importance. The former method is known as the Modified Mercalli Scale. This uses Roman numeric classification from I to XII to describe the intensity based on the impact to the surroundings. For example, Category I refers to an event detectable only by instruments, while Category XII implies almost complete destruction.

In contrast to the Mercalli Scale, the Richter Scale is determined by instruments and measures the quantitative magnitude, or strength of an earthquake on a logarithmic scale. The logarithmic nature of the Richter Scale is often overlooked by lay people and news reporters. An increase of a unit in Richter classification is equivalent to an increase by a factor of 10 in amplitude of movement, or by a factor of about 30 in energy released.

An approximate correlation between Richter Magnitude and Practical Intensity is provided in Table 2-1.

TABLE 2-1

Correlation Between Richter Magnitude and Practical Intensity

Richter Magnitude	Practical Intensity
1	Detectable only by instruments
2	Barely perceptible even near epicenter
4.5	Detectable within 20 miles of epicenter
6	Moderately destructive
7	A major earthquake
8	A great earthquake

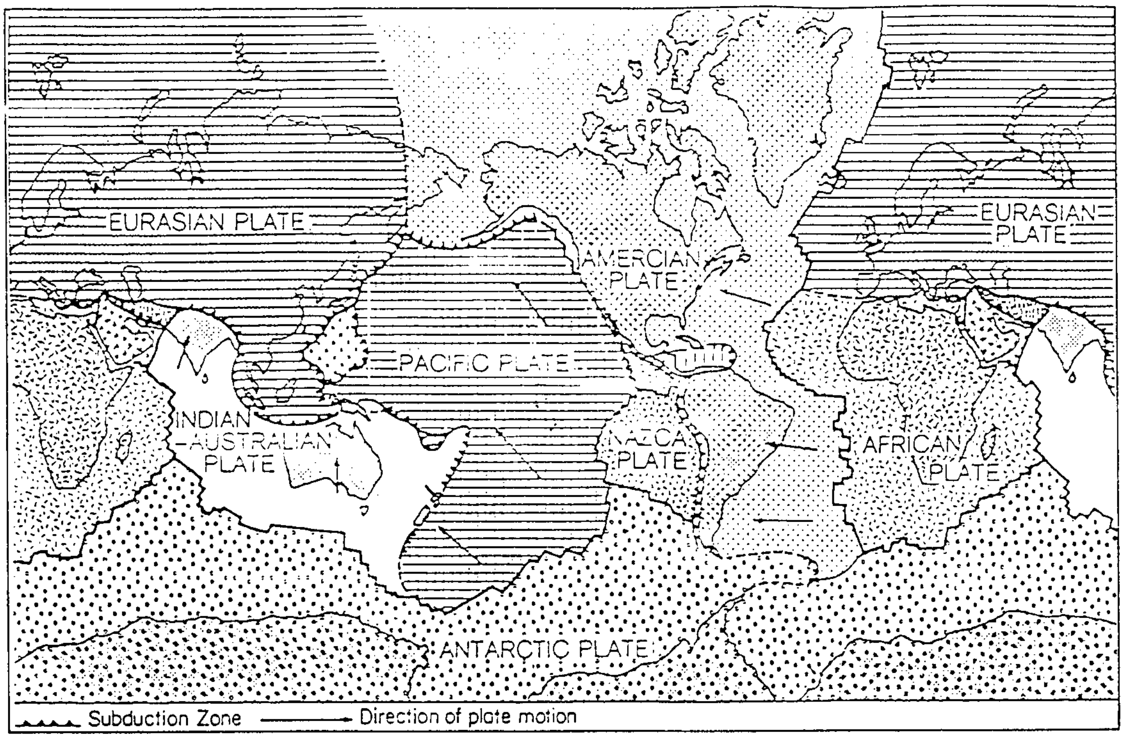

Figure 2-1 Tectonic Plate Map of the World

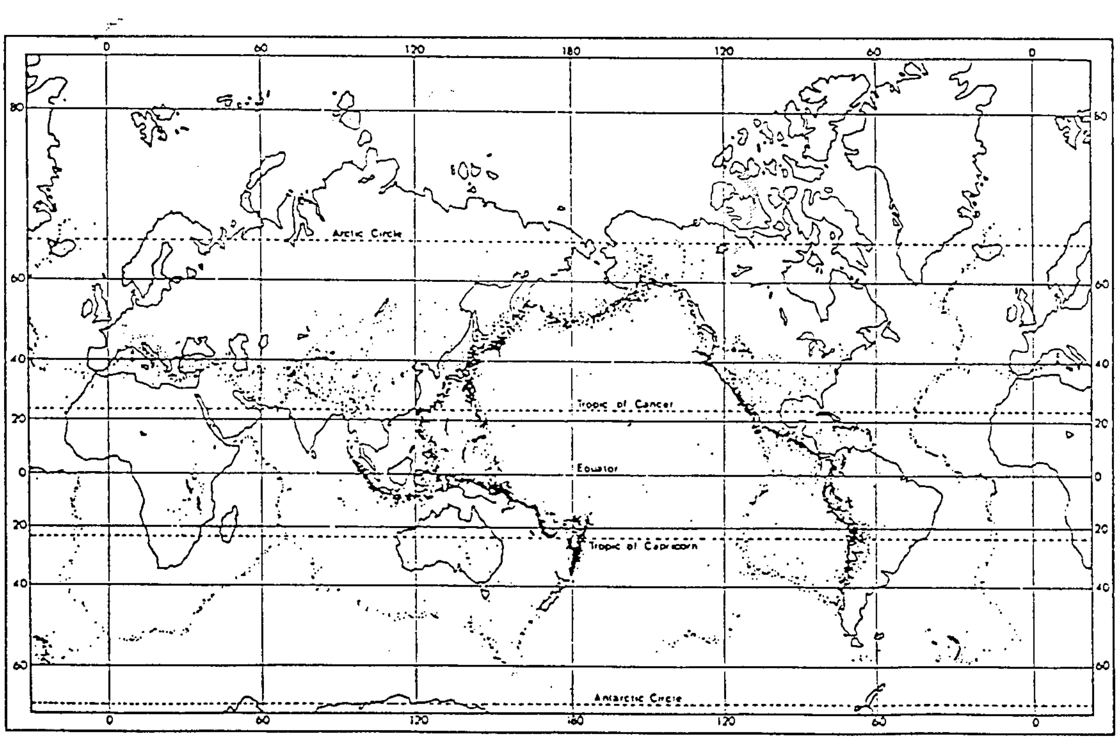

Figure 2-2 Worldwide Earthquake Distribution

2.2 Earthquake Regions

Although the earth's internal forces exist over the whole spherical surface, the resulting geological disturbances do not occur uniformly. Most earthquakes occur in certain narrow earth-encircling belts separated by relatively stable blocks (plates).

The concept of global tectonics is based on an earth model characterized by a small number (10 - 25) of large thick plates composed of both continental and oceanic crust (see Figure 2-1). Each plate "floats" on a viscous underlayer and moves independently of the others, grinding against them at the common boundaries. The boundaries of the major plates coincide well with the epicenters of most frequent earthquake activity (see Figure 2-2). The circum-Pacific belt is by far the most important, accounting for about 80% of total earthquake and volcanic activity. This belt is effectively the perimeter of the Pacific plate whose eastern boundary is along the west coast of North America, and whose western boundary includes Japan and New Zealand.

Within the United States, the observation and recording of seismic events has led to the development of maps which categorize areas by their seismic activity and level of risk. The Seismicity Map of North America, prepared by the U.S. Geological Survey, graphically shows the historical earthquakes by location and magnitude throughout the North American continent. The distribution is very nonuniform with by far the greatest concentration of activity along the western coast.

Specifically, very high seismic activity (both in frequency and magnitude) has been experienced in Alaska and the Aleutian rim, and just off the coast of Canada near Vancouver Island. The state of Washington shows some activity as does the area around the Idaho and Wyoming borders with Montana. Of the contiguous states, California has been the most active, with high concentrations of activity in the areas south of San Francisco, and the southern part of the state.

Within California the dominant geological feature actively generating earthquakes is the San Andreas Fault System, extending in a north-south direction over the entire length of the state. This system has received worldwide attention because of its history of significant activity and because it passes through some of the most populated parts of the country.

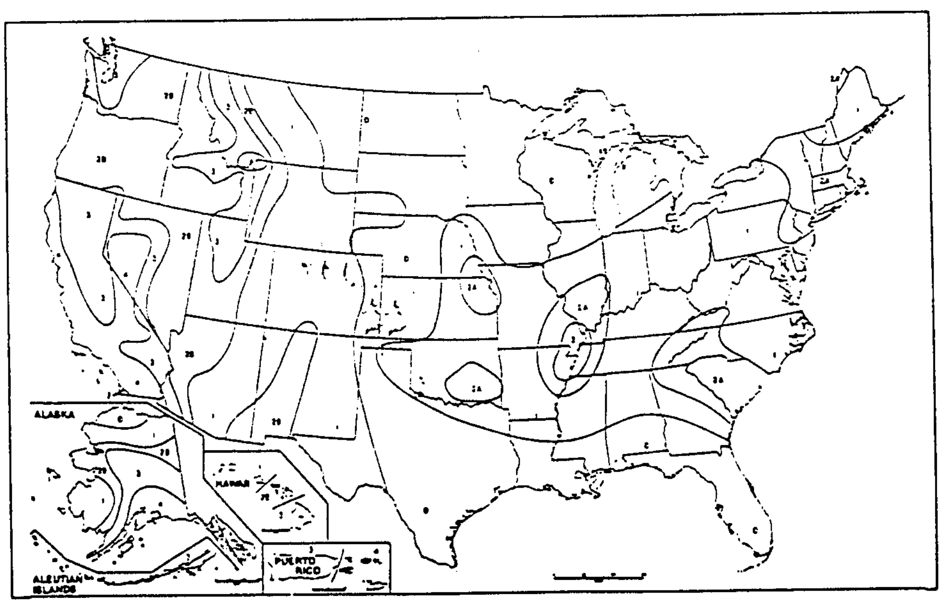

Figure 2-3 Seismic Zone Map of the United States (UBC - 1991)

Western states such as Nevada and Utah show a low to moderate amount of activity; otherwise, the internal parts of the country have been relatively quiet. A concentration of activity which looks a little out of place is near the borders of Tennessee, Kentucky, and Missouri. This is the area of the New Madrid Fault.

Although it is true that earthquakes are more probable in some areas than others, it should be recognized that all states have at least some potential for activity. The problem of earthquakes should therefore never be ignored. It is not exclusively a west coast matter.

Maps such as that shown in Figure 2-3 indicate the levels of risk associated with different areas of the country. Figure 2-3 shows the Seismic Zone Map of the United States used by the Uniform Building Code. The level of risk increases with the seismic factors ranging from 0 to 4. Similar maps are used by other codes; some indicate the expected ground acceleration, others simply indicate a zone factor, or category, which is used for design.

2.3 Potential Impact of Earthquakes

The impact of earthquakes of most concern to us is damage to property and possible loss of life. We have seen historically that the most dangerous aspects of seismic activity are the effects it has on man-made structures. Most deaths in recent times are not the direct result of the earth's actions, such as ground shaking, volcanic eruption, or tidal waves, but the result of the failure of the man-made structures we live and work in. Failure of infrastructures such as buildings, highways, and transit systems, exposes the population to direct risks of injury and death. In addition, there can be longer term social problems associated with disruption of communications, vital services, and the damage to utilities. In the 1906 earthquake in San Francisco, most of the damage and loss of life resulted from the ensuing fire and the inability to control it.

The structures we build are supported on foundations built into the soil or rock mass. Movement of the soil or rock, and therefore of the foundations, results in movement of the structure. The associated accelerations induce forces within the structure. If the forces exceed the capacity of the structural members, damage results. If the damage is extensive enough and the member is critical to the integrity of the structure, total failure or collapse may result.

An earthquake can influence a structure in two ways. The first is by massive failure of the surrounding soil, such as movement of a fault, liquefaction, or gross settlement. This can often be avoided since the site's predisposition for such extreme behavior can be determined in advance. The second influence is the actual shaking of the earth and the pressures and displacements it imposes on the structure. For in-ground facilities, a structure is confined and therefore supported by the soil mass. Its deformation is therefore limited to that of the soil. For aboveground facilities, the flexibility of the structure can result in amplified responses, which actually exceed the movement of the soil.

In the design of structures, allowances are typically made for all of the anticipated forces. The dominant forces are usually those associated with gravity acting on the structure itself and on the occupants. Fortunately the magnitudes of such loads are fairly predictable and so it is easy to allow sufficient capacity. With seismic loads, however, it is far more difficult to make the proper allowances because of the unpredictable nature of earthquakes. Although historical observation of earthquakes tells us that certain geographical areas are more likely than others to experience quakes of significant magnitudes, it is not possible to accurately predict the time or location of an event, or its intensity and characteristics. The design for earthquakes must therefore be approached from a probabilistic viewpoint. One method often used in earthquake design is the response spectrum which defines the likely response of simple structures to a particular earthquake.

3. SEISMIC PHILOSOPHY

3.1 Historical Development of a Seismic Approach

Although earthquakes have always been a part of human experience, it is in fact only recently that a scientific approach has been taken to allow for them in construction. Even now, recognition of the importance of seismic consideration is by no means uniform throughout the world. High levels of damage and death have often been the result of the wrong form of construction in seismically active areas. Recent tragic events such as Mexico City (1985) and Armenia (1988) should increase people's awareness, and expand the emphasis on developing more suitable building standards. In this country, the history of seismic design can be seen in the evolution of the national and state codes. The codes of construction generally reflect the industry's conviction regarding appropriate technical standards.

The chronology of events related to the development of the current codes is well described in Reference 2. In this chronology we can trace the evolution of certain key ideas. Initially, no earthquake provisions were made. Later there was a recognition that earthquake motion induced horizontal forces which were in proportion to the mass of the structure. An early criterion assumed that earthquake loads could be represented by static horizontal forces whose magnitudes were percentages of gravity loads. The importance of constructing sound structural details was recognized (an early acknowledgment of the importance of ductility), and the concept of retrofit emerged as a means of improving the earthquake performance of existing structures.

The concept of geographic zoning, based on seismic risk, was developed, as was the recognition that not all earthquakes are equivalent in their impact. For example, a structure may be allowed to suffer a greater amount of damage in the case of a large and improbable earthquake than for a smaller but more frequently occurring event. Likewise, not all structures are of equal importance. Some, because of social or strategic reasons must remain functional under all conditions. For other less important examples, damage may be acceptable.

Perhaps the most revolutionary breakthrough in the development of current codes is that which emerged from the studies made by the Applied Technology Council (ATC-6) in the late 1970s. This recognized that it is not practical to try to suppress displacements, and that the key to design is to allow sufficient ductility so that the structure can deform without collapsing. In permitting such deformations, it might be necessary to accept limited damage to certain structural members.

In most published seismic literature, the discussion is largely confined to aboveground structures. Very little guidance exists for the seismic design of underground facilities. The reason is that it is more difficult to develop nationwide tunnel standards when so much depends on site-specific geotechnical conditions. Fortunately, tunnels are generally not as susceptible to earthquake damage as aboveground structures.

Perhaps the most interesting observation made in reviewing the historical development of seismic design is that so many of the relevant breakthroughs have been made very recently (the last 20 years). Indications are that we can expect this evolution to continue, as the key concepts are refined.

3.2 Design Philosophy

Structures are designed to safely accommodate the forces and displacements they are likely to experience. Most loads are relatively easy to estimate and therefore to allow for. Earthquake loads are different because of the uncertainty of occurrence and their unpredictable nature. No-one would question the need to design a structure to remain totally free of damage under its own weight (dead load) or under frequently occurring live load (people, vehicles, etc.). Is it justified, however, to invest in provisions for a very large and improbable earthquake? Clearly, a different philosophy must be taken for seismic loads, one which recognizes their probabilistic nature.

A common philosophy in seismic design is to make different provisions for events of different severity, recognizing the different probabilities of these. Typically two seismic events are defined for a specific site. The larger of the two earthquakes is meant to represent an event that has a very low probability of occurring during the life of the structure. The smaller earthquake would be expected to occur.

Since the smaller earthquake is in the category of likely events, the structure should be designed to withstand it with little or no structural damage. The loads for this event are, therefore, treated in a manner similar to dead and live loads.

In the case of the larger, less probable earthquake, it is expected that limited structural damage will occur. The damage should not, however, result in the collapse of the structure, and should be detectable and repairable. The degree of damage that can be accepted is a matter of policy. For less important structures, a major repair or even replacement may be acceptable. For vital structures, the acceptable damage would be minimal. In all cases, the emphasis is to avoid a total collapse and the related threat of injury and loss of life.

The larger and smaller earthquake events are often called the Maximum Design Earthquake (MDE) and the Operating Design Earthquake (ODE) respectively.

The treatment of elevated structures such as bridges or viaducts can follow one of two approaches. The traditional method involves the application of equivalent static loads which are derived by factors related to the nature of the soil, the geographic region, and the type of structure. The alternative method is to calculate the anticipated forces, and then to reduce these by a factor to determine the design forces. Since the design forces are lower than the realistic levels, the structure would yield during the assumed earthquake, and incur damage. The level of damage would be proportional to the reduction factor used.

Underground structures can also be treated in two ways. The more traditional approach is to estimate the incremental earth pressures generated in an earthquake and apply these to the structure. This is a "load approach." The other method, or "displacement approach" is to assume the structure will deform as the soil. The design, therefore, must give the structure the capacity to deform adequately without risking collapse. The "displacement approach" may be less applicable if the soil is very flexible or weak. In this case the deformation of the soil could be influenced by the structure, resulting in a displacement pattern which is less than that of the free-field soil. This interaction between the soil and the structure is very difficult to calculate, and guidelines are still being developed.

In some cases, the approach taken to earthquake protection involves the isolation of the structure from the earth by use of flexible mountings. This can dissipate energy and partially free the structure from having to follow high frequency ground displacements. Although, there are many examples of applications in Japan, Europe, and New Zealand, there are concerns that isolation techniques could be accompanied by excessive displacements under both conventional and earthquake loads. It is therefore not commonly used in the United States.

The term "seismic retrofit" is used to describe the process of attempting to improve the potential earthquake performance of existing structures. To date, most activity in this area has been confined to highway bridges. The 1971 San Fernando earthquake illustrated many deficiencies in bridge design. In addition to inspiring research into the design code improvement, the earthquake also raised the question of what could be done to improve the seismic performance of existing bridges. After the San Fernando earthquake, FHWA conducted a study with the objective of identifying and defining practical techniques for implementing physical improvements to existing bridges. The aim was to increase the probability of survival of the structure in an earthquake. The resulting document was a 1983 report entitled " Seismic Retrofitting Guidelines for Highway Bridges."

It is, however, generally very difficult to improve the seismic capacity of structural members after a facility has been constructed. Furthermore, it is usually not simply a lack of strength that places a structure at risk, but inadequate detailing of joints and other components. These are not easily modified after-the-fact.

As an example, the Alemany double deck interchange between Highways I-280 and 101 in San Francisco is currently undergoing retrofit. It was originally believed that using pressure-grouted steel jackets to confine the columns, and prestressing tendons to strengthen the joints would provide adequate reserve strength to prevent collapse during an earthquake. After detailed review, however, it was concluded that the original structure lacked adequate detailing to allow for the ductile behavior required in a strong earthquake. The conclusion was that all structural members except for the box-girder decks should be replaced by or strengthened with new members which meet the strength and detailing requirements of the latest guidelines.

Overall, retrofit is expensive, except for the simplest restraint devices, and often impractical. In some cases the only practical way to avoid the potential for catastrophic collapse is to partially or completely rebuild the structure. Clearly it is far more desirable to include appropriate provisions at the time of construction.

4. CURRENT DESIGN GUIDELINES

4.1 General

Many codes, standards, and guidelines exist, which address seismic design of various facilities. The two codes most widely used in the United States are:

- The Uniform Building Code (UBC) published by the International Conference of Building Officials.

- The Standard Specifications for Highway Bridges published by the American Association of State Highway and Transportation Officials (AASHTO) (Reference 4).

The UBC addresses buildings and their contents, towers, chimneys, tanks, signs, and other above-ground structures. The AASHTO seismic criteria address highway bridges and earth retaining structures such as abutments and retaining walls. A host of other local building codes and department of transportation criteria also exist. Most of these incorporate the general requirements of at least one of these two codes, with modifications made for local issues. However, neither of these national codes address specifically, or by inference, mass transit facilities.

Mass transit authorities in seismically active areas have often developed seismic criteria specifically for their systems. These criteria are usually developed from the most applicable portions of UBC and AASHTO; previous design criteria developed for similar projects, and information developed for that specific project. AASHTO has been used primarily for the design of elevated guideways (i.e., bridges) and retaining walls. UBC has been used for the design of aerial station appendages such as canopies, elevator shafts, stairs, etc. UBC has also been used for the design of at-grade stations, maintenance/support buildings and their contents (i.e., traction power equipment, communication equipment, etc.). and the equipment in subway stations. Neither of these codes, however, addresses seismic design of underground structures.

Seismic criteria for underground facilities have evolved outside of the realm of UBC and AASHTO. For virtually all projects located in seismically active areas in the U.S., the design guidelines have developed on a project-specific basis. From the early days of the Bay Area Rapid Transit System (BART) to the most recent Los Angeles Metro Rail Project, seismic criteria for subways have been developed for each project.

4.2 American Association of State Highway and Transportation Officials (AASHTO)

AASHTO has been used primarily for the design of elevated guideways, stations and retaining walls. The basic parameters in the AASHTO guidelines include:

- Four specific Seismic Performance Categories (SPC).

- Site effects for different soil profiles.

- Response modification factors.

The seismic performance categories are determined by the assigned acceleration coefficient and the structure's importance classification. The acceleration coefficient varies throughout the United States. The importance classification portion of the seismic performance category classifies bridges as either "essential bridges" or "other bridges." Classifications are determined by social/survival and security/defense requirements. These requirements are outlined in the AASHTO Specifications.

Simply put, essential bridges are those that must keep functioning during and after an earthquake. Consideration of both the acceleration coefficient and importance classification translates into a specific seismic performance category A, B, C or D. SPC A is the lowest risk category. The risk increases to D, the highest risk.

Site effects reflect the varying geology at different sites. The seismic response generally increases with the amount of soft and medium-stiff sands and clays near the surface. It is important to note that these site effects are very general. At specific sites near faults or with a potential for landslides or liquefaction, the recommendations within AASHTO must be supplemented by more stringent requirements.

The response modification factors quantify a structure's ability to withstand large displacements without collapsing (ductility). The more ductile a structure, the more likely it will "ride out" an earthquake as long as it does not slip off its supports.

Embodied in the AASHTO guidelines are also specific requirements for superstructures and substructures, in both concrete and steel construction. The result is a unified document that addresses the seismic design of highway bridges. Owners and designers of elevated mass transit facilities in the United States generally agree that the basic AASHTO guidelines, or, in the State of California, the Caltrans guidelines, are a good basis for the design of aerial mass transit structures.

4.3 Uniform Building Code (UBC)

While AASHTO, Caltrans, and FHWA were developing seismic criteria for bridges, the International Conference of Building Officials (ICBO) and the seismic committee of the Structural Engineers Association of California (SEAOC) were developing seismic criteria for buildings. Over the years, UBC and AASHTO matured along the lines of "distant cousins." Both recognized that the probable intensity of earthquakes varied throughout the country. They also recognized the fundamental importance of ductility. Each approached the matter somewhat differently however. In 1991, the UBC adopted a format and approach similar (but not identical) to AASHTO's.

UBC includes seismic criteria for buildings and their contents, towers, chimneys, tanks, signs and other aboveground structures. In determining the seismic response of a structure, UBC uses variables similar to AASHTO's. These include:

- Seismic zone
- Occupancy categories
- Site coefficients
- Structural system response factors

The seismic zone category varies from 0 through 4. Zone 0 is the lowest risk area while Zone 4 is the highest risk area. The geographic definition of these zones is very similar to AASHTO's. (See Figure 1, Section 2).

The occupancy categories in UBC are similar to AASHTO's importance classification. These are:

- Essential facilities
- Hazardous facilities

- Special occupancy structures
- Standard occupancy structures

The structural system response factors and site coefficients, while not numerically the same as AASHTO's, are similar in principle.

UBC has been used by owners and designers of mass transit facilities for the design of aerial station appendages such as canopies, elevator shafts, stairs, etc. It has also been used for the design of at-grade stations, maintenance/support buildings and their contents (i.e., traction power equipment, communication equipment, etc.), and the equipment in subway stations. As with AASHTO, the UBC has become a good basis for the design of these facilities.

Since these codes do not specifically address mass transit facilities there has been much interpretation in their application. For example, what importance factor or occupancy classification should be assigned to a transit system in general? What amount of damage, if any, is acceptable to emergency systems such as power and ventilation? These questions, and many others have been often asked, but usually in the context of a specific project.

5. CURRENT PRACTICE

5.1 Categories of Transit Structures

Public transportation systems around the country include a variety of technology types and related variations in fixed facilities such as guideways, stations, and maintenance/storage areas. The type of fixed facility selected depends upon cost, operations factors, and relevant constraints. What the facilities have in common is their exposure to damage in the event of an earthquake.

Failure or collapse of transit facilities carrying large numbers of people cannot be tolerated. Further, sufficient damage to prevent operations for a significant time after an earthquake can have a very disruptive impact on a community. The importance of maintaining public transportation after an earthquake was demonstrated in the Loma Prieta earthquake that shook the San Francisco Bay area in October 1989. The damage sustained to the Bay Bridge (see Figure 5-1) and other highway elements severely disrupted automobile and bus traffic. The rapid rail system (BART), housed within an immersed tube tunnel under the bay, became the main means of conveying the many thousands of daily commuters from the east bay to downtown San Francisco. A description of this event is included in Appendix 1.

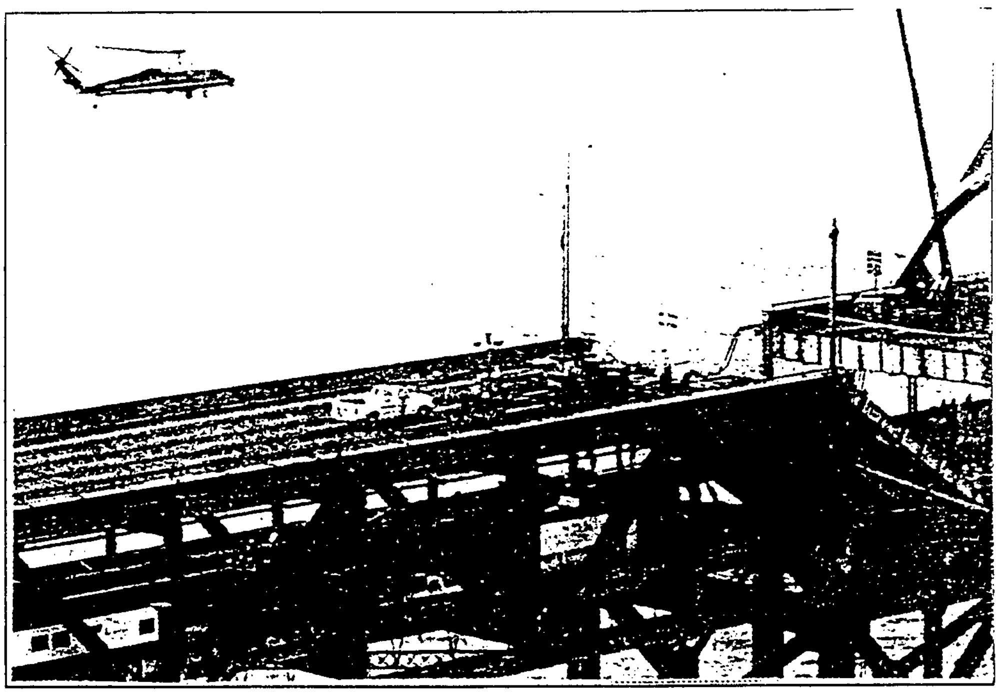

Figure 5-1 Oakland Bay Bridge After 1989 Loma Prieta Earthquake

For the purpose of discussing earthquakes, the following categories of transit structures can be defined.

- Aerial structures
- Underground structures

- Maintenance facilities and utilities

Aerial structures include elevated guideways or viaducts and aerial stations. Underground structures include tunnels (cut-and-cover or bored) and underground stations. Maintenance facilities typically include low (one-or two-story) light industrial buildings and outside vehicle storage areas. Transportation systems also require utilities for their operation. These may include gas, power, water, wastewater service, and drainage. Bus maintenance facilities may include underground fuel storage tanks and fuel lines. Also, electrically powered transit systems will include power distribution facilities. Utilities are exposed to earthquake damage as are the structures, and their failure can lead to situations which are hazardous, and disrupt service.

5.2 Current Practice - General

In general, existing national and local codes are used for the applicable structural types, as discussed in Section 4. For cases where relevant local or national codes are not available, project specific design criteria are developed. Most recent major transit projects, including the LA Metro, the Downtown Seattle Transit Tunnel, and BART extensions, have used a combination of existing codes and project specific criteria.

5.3 Seismic Design Methodology for Underground Facilities.

Underground facilities such as subway tunnels and stations are in general not under great risk of damage by earthquake ground shaking, although they are susceptible to the rupture of active faults or the general failure of the surrounding soil mass. The potential for these phenomena, however, can often be determined by geotechnical investigations of the site.

It is not common for an underground facility to cross a fault plane, and it is not practical to design the structure to resist its rupture. If active faults cannot be avoided, the structure must be designed to accommodate a certain amount of displacement. If a modest displacement can be absorbed without causing structural distress, the structure has a much better chance of surviving an earthquake. This is the recent experience with the BART Trans-bay tunnel. Flexible joints were included in the structure as part of the seismic provisions. The structure sustained no damage in the 1989 Loma Prieta earthquake.

The common impact of earthquakes on underground facilities is the fluctuating deformation imposed on the structure by the vibrating soil. The current seismic design approach calls for two-tiered design earthquakes. This includes the Maximum Design Earthquake (MDE), and the Operating Design Earthquake (ODE) introduced in Section 3. Under the MDE, the aim is to prevent catastrophic failure. Local yielding of the steel and cracking of the concrete may be permitted as long as it is repairable and does not erode the structure's ability to carry load. In the case of an ODE, higher than usual stress levels can be permitted because of the low probability of the event. The structure should, however, suffer little or no damage.

The seismic design of an underground structure is based on the deformations of the surrounding soil and rock. It is not realistic to assume that a structure can resist the deformations. The general approach is to assume that the structures are flexible relative to surrounding soil and move in accordance with its free-field deformations. The structures are designed to accommodate these deformations without losing their stability. This approach was conceived by Tom Kuesel in 1969 (reference 12). It is generally applicable and leads to good design solutions in rock or stiff soil. In the case of soft soils, however, the free-field displacement is greater than a structure could be reasonably expected to accommodate.

5.4 Seismic Design Methodology for Elevated Structures

As noted in Section 3, perhaps the most significant review and revision of the approach to the seismic design of bridges occurred as a result of the 1971 San Fernando earthquake near Los Angeles. Because of the many bridge failures on the Golden State Highway, FHWA sponsored research that included the work of the Applied Technology Council, which published the ATC-6 Seismic Design Guidelines for Highway Bridges in 1981 (reference 5). These were adopted by AASHTO as "Guide Specifications for the Seismic Design of Highway Bridges" in 1983.

Prior to this time, typical bridge design used a lateral force coefficient to represent the lateral earthquake load. The coefficients were, however, much lower than the actual earthquake forces and failed to make adequate allowances. On the other hand, the more realistic earthquake forces calculated from response spectra were too large for practical use in design.

The research led to a new approach to seismic design that treated earthquake loads differently than the more conventional dead and live loads. For most loads, a structure is designed to have a capacity which is equal to the imposed loads plus an additional reserve, or safety margin. The lateral forces in a major earthquake are so high that to take a similar approach would be uneconomical and impractical. Therefore, it is accepted that it is not necessary to design the structure to remain elastic during a major earthquake. Instead, the structure may be allowed to yield, that is to absorb limited damage, provided that catastrophic collapse is prevented and that the damage be relatively detectable and repairable.

The key to the new design approach is structural ductility, the property of a material which allows it to deform beyond its elastic range without breaking. Correctly designed reinforced concrete structures can achieve a very high degree of ductility. This requires careful detailing of the reinforcement and good quality control during construction.

5.5 Transit Projects - Examples

As an indication of how differently projects have considered the seismic issue, the following describes some recent examples. The differences in emphasis and the diversity of approaches is apparent.

BART Extension

The BART system was the first of the new generation of rapid transit projects in this country, and is located in a very active seismic region. At the time of its design in the 1960s, few seismic guidelines were available, especially for underground structures. Kuesel proposed the "displacement" approach, which recognized that a tunnel could not be made to resist the deformation of the ground, and therefore should be constructed to accommodate the deformation. This effectively meant that the structural members should be as flexible as possible consistent with having the capacity to resist the permanent loads.

Also considered was the fact that structures of different properties may behave differently in an earthquake. Therefore, at the connection of the relatively flexible immersed-tube tunnel to the rigid ventilation building, moveable joints were constructed. Thus, the two structures could respond differently while still holding together. After the Loma Prieta earthquake, the BART tunnels were inspected. Movement at the flexible joints had occurred, but since these had not been continuously monitored over the service life, it was not conclusive as to whether the displacement was due to the quake or to accumulated movements over the years.

With the current design of the line extensions, BART has developed new criteria which are generally more stringent than those used for the original design. The basic principle behind the criteria is that the transit system is vital to the area, and so must remain fully operational after a major earthquake.

Site-specific earthquake information was developed for BART by seismic specialists. In particular, the maximum credible earthquake was determined to be that with a Richter magnitude of 7.0 originating on the Hayward Fault. A horizontal acceleration of 70% gravity was selected along with specially developed design spectra for the applicable soil classifications. The basic code used for the design of the elevated structure was the Caltrans Bridge Design Specification modified to reduce the level of acceptable damage in a quake.

For the underground structures, BART chose to use an earth-pressure approach rather than the displacement approach used by the L.A. Metro Rail Project. The reason is that the BART tunnels are quite shallow and the soil is soft, making the displacement method less applicable.

San Francisco Municipal Railway - MUNI

The San Francisco Municipal Railway is a light-rail and bus system serving the City of San Francisco. The rail operates both in underground and surface conditions while the buses operate in mixed traffic on the city streets. Since the original construction, the system has seen many extensions and upgrades requiring the construction of new guideway and maintenance facilities. In 1981 the downtown segment was converted from surface to underground operation. Recently some of the lines have been extended and there are now plans for a new maintenance facility.

MUNI does not have its own seismic design criteria, but relies on the San Francisco City Code, which is based on the California Building Code. Under this code, a structure is expected to suffer no structural damage and limited nonstructural damage during a low-intensity earthquake, minor structural damage and moderate nonstructural damage during a moderate earthquake, and major damage but no collapse during the strongest expected earthquakes.

Clearly this criteria is less restrictive than that now adopted by BART, and it appears less likely that operations could quickly resume after a major earthquake. The system did perform well however during the 1989 earthquake and suffered no damage. It should be noted that MUNI has no elevated guideway structures.

Los Angeles Metro Rail

In this project, which is predominantly underground, it is again recognized that the main effect of an earthquake on underground structures is the imposition of a deformation that cannot be substantially changed by strengthening the structure. Therefore, the structural design solution was to provide sufficient ductility to absorb the deformation without losing the capacity to carry static loads. If it was established that the maximum deformation imposed by an earthquake, when combined with other appropriate loading, did not strain the structure beyond the elastic range, no further provisions were required. If parts of the structure were expected to experience yield, the ductility of the structure was investigated.

As for the BART Project, an operating design earthquake (ODE) and a maximum design earthquake (MDE) were defined and ground motion accelerations were established.

Taipei Metro Rail Transit Project

The design criteria for the Taipei MRT project was developed in a similar way. Site-specific seismic data was developed by earthquake specialists and the peak ground accelerations were defined. The Taipei Basin is considered a milder earthquake region than California, and peak ground accelerations of only 18 percent were recommended. The project used the same approach to elevated structures as BART, but without the especially strict value of the force reduction factor. The approach to the underground structures was the same as the L.A. Metro Rail Project.

MARTA - Atlanta

This system was designed in the early 1970s using AASHTO as the governing code, and Zone 2 for the definition of seismic activity level. Additionally, the criteria required that all structural connections be designed for 10% of gravity loads. This requirement recognized that connections are usually the weak links within a structure, and are often the cause of failure during an earthquake. Other than the above, no other seismic provisions are made. Earthquake loading did not control the design.

Extensions to MARTA are currently under design. The criteria has not changed since the original design and so presumably, the same seismic approach will be used. It is interesting to note, however, that Fulton County, in which an extension is located, is considering upgrading its seismic zone classification. This may influence MARTA's approach in future construction.

WMATA - Washington, D.C.

Because of the low zone classifications for this area no specific provisions were made in the design of this system. The common codes of practice were followed.

Santa Cruz Bus Facility

The bus maintenance facilities for Santa Cruz, California, provide an interesting example because of their exposure to the Loma Prieta earthquake. There are two facilities, one in Santa Cruz, and the other in Watsonville. Both areas were severely impacted by the earthquake.

The building in Santa Cruz is a steel framed Butler Building erected in the mid-1980s and designed to the Uniform Building Code. It performed very well during the earthquake, suffering only minor architectural damage. The operations within the building could be resumed immediately after the earthquake.

In contrast, the building in Watsonville suffered major structural damage and was condemned. This facility was constructed of reinforced concrete in 1982. Post-earthquake studies indicate that the design of the building failed to meet the requirements of the building code, and so did not have an adequate level of protection against damage. The problem was compounded by some liquefaction of the soil on one side of the building.

Even if the UBC code is applied in the design of a maintenance facility, there may be a problem if the structure is given a low importance factor. Often this is done because maintenance facilities may be considered non-critical or non-life-threatening. Maintenance facilities are, however, critical to the operations of a transit system, and merit greater consideration.

Hartford Bus Maintenance Facility

The Hartford Bus Maintenance Facility Building is a steel framed structure with a combination of steel and precast concrete siding panels. This facility was constructed in 1989 and opened for occupancy and operation in the spring of 1990. Many municipalities and local government agencies, including the City of Hartford, use the Building Officials and Code Administrators (BOCA)

International, Inc. National Code for seismic design criteria. In the absence of project-specific design criteria, the design engineer used the 1987 edition of BOCA for seismic considerations for the maintenance facility. The facility was designed for Zone 2 seismic criteria as defined in the 1987 BOCA edition. The zone designation of the 1987 BOCA edition is similar to the designations shown on the UBC Seismic Zone Map (see Figure 2-3). The design engineers indicate that the seismic design considerations for this facility had virtually no effect on construction costs.

Since construction of this facility, BOCA revised its seismic design criteria for buildings and structures in its 1990 edition, and in its 1992 Supplement it removed the seismic zone map and inserted in its place an Effective Peak Velocity (EPV) Coefficient Contour map, which provides design criteria for the various regions of the country, as well as a revised design procedure.

6. RELEVANT RESEARCH

Just as seismic engineering has evolved greatly in the past few years, the field is still changing with research and development continuing. The volume of research, at both the academic and design levels is considerable, and there is no attempt here to cover more than just a representative sample. Some of the research efforts are aimed at improving the codes of practice while others investigate specific sites in an attempt to better understand their seismic risk.

A paper by Mayes et al, presented at the Third Bridge Engineering Conference in Denver, Colorado in March 1991 (reference 7), presented concepts related to improving the design of bridges by adopting some variations to the AASHTO approach. The AASHTO specification requires an analysis for only the maximum earthquake, and all of the forces and displacements are derived from this. Thus, the behavior for the more probable lower magnitude earthquake is not directly addressed.

In the two-level approach proposed in the paper, an analysis is performed for both the upper level and lower level seismic events. The upper level can be the maximum credible earthquake or one with a very high return period (e.g. 2500 years). The lower level event could be one with a return period of 72 or 150 years. The results of the lower level analysis would be used together with the conventional loads to ensure that there is no significant damage. This way, the analysis directly considers the behavior of the structure both in the extreme case and also in the case that is likely to occur.

This approach is currently required on all essential facilities for the Department of Defense and is proposed for the design of bridges on the Orange County Toll Road Project.

As discussed in Section 5, Kuesel's 1969 paper was a pioneering effort which changed the approach to seismic design of underground structures, particularly subway tunnels for transit. Since that time, however, seismic design concepts have not progressed significantly. Current research aims at refining Kuesel's concepts to be more suitable over a wider range of tunnel and soil types.

Kuesel's paper is based on the assumption that the soil or rock surrounding the structure is stiff compared to the structure, and that the structure must conform to its free-field deformation. Since this approach is simple and generally conservative, it is widely used, particularly when the soil is reasonably competent. In soft soil, however, this approach may be overly conservative. This problem was encountered during the design of the Taipei Metro and the Boston Central Artery. The solution is to adequately model the soil/structure interaction, and therefore account for the influence of the structure on the deformation of the soil. Research in this area is currently being conducted by Wang.

There are few cases where transit facilities cannot avoid crossing an active fault zone. One such example is the BART tunnel system crossing the Hayward Fault. At BART's request, the University of California prepared a report (reference 17) to discuss the behavior of the tunnels crossing the fault. The concern was the structural integrity of the system and the impact of any tunnel movement on track alignment. Clearly it is not practical to design a tunnel to suppress fault movements and ideally the structure can be made to accommodate a limited amount of deformation. As the tunnel deforms, however, so does the trackway within it. In some cases slight realignment of the track may be necessary to restore alignment tolerances.

In the case of the BART tunnels, the original design was concerned with fault rupture. At that time it was believed that if the fault movement were distributed over a tunnel length of about 100 meters, track realignment was feasible without the need to expand the tunnel size. Throughout the fault zone, rails were supported on wooden ties instead of the typical concrete bedding. This would facilitate track realignment if necessary after fault movement. Since 1968, 80 mm of lateral displacement has occurred, resulting in track distortion and cracks in the tunnel lining. This has been detected through monitoring instrumentation installed at the time of construction, and by later surveys. To date this has not caused structural or operational problems to BART. It is strongly recommended that for distortion-sensitive systems built in fault zones, careful and comprehensive monitoring of movements be implemented.

Increasing awareness of the danger of earthquakes is causing transit agencies and other public bodies to assess their risk and to develop mitigation measures and contingency plans. It is specifically recognized that there are certain vital services, or lifelines, which must remain operational after a major earthquake so that relief activities can proceed.

As an example, western Kentucky is located in the New Madrid rift zone which has a probability of 86-97% that an earthquake of magnitude of 6.3 will occur within the next 50 years. Because highways are the primary source for the delivery of emergency supplies to an earthquake zone, the transportation cabinet of Kentucky wants to select priority routes for all of the 26 counties that are within this zone to be kept passable after an earthquake (see Figure 6-1). The objective is to develop seismic risk maps of all natural and man-made features that are susceptible to seismic damage. These features will be analyzed and safeguarded against damage and their personnel trained in seismic safety. The latest U.S. seismic codes would be used in the construction of any new facilities.

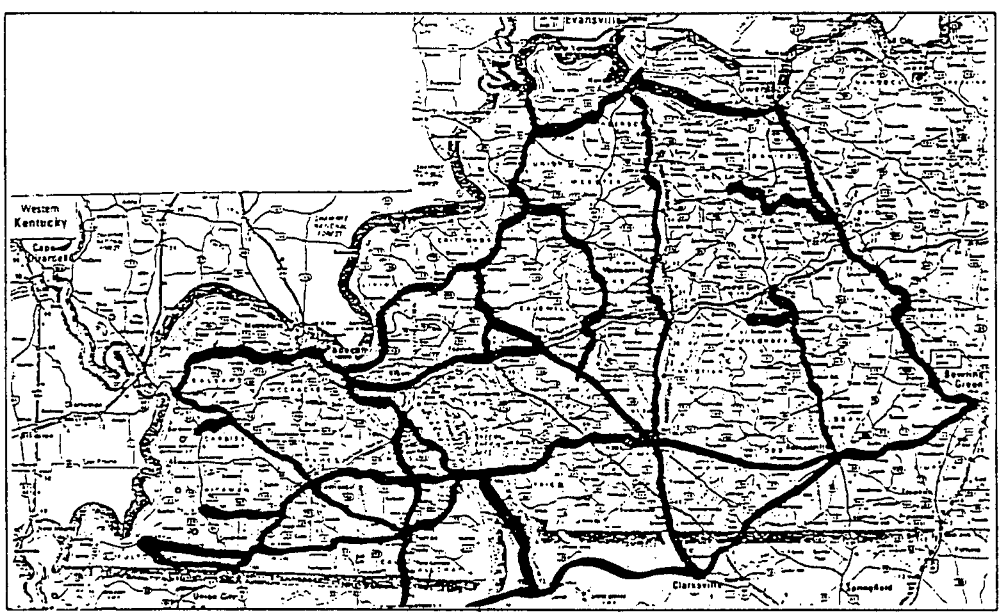

Figure 6-1 Recommended Priority Routes, 26 Counties, Western Kentucky

D.L. Allen (reference 9) describes the selection of the vital routes and catalogues the features along those routes that could represent potential problems during a quake. The features include buildings, dams, power lines, and bridges. Review of the bridges indicated that of the 350 in the system, about 130 may require retrofit. Allen recommends specific improvements to the structures and includes estimated costs.

Many of the transit facilities in this country were built before the development of modern seismic guidelines. Now, with increased interest and knowledge of earthquakes, there is some reassessment of the actual risks. A recent study was made by the University of New York, reviewing the anticipated performance of the New York City elevated transit lines. The study is described in a paper by Costantino (reference 11).

Both soil and structure behavior over an expected range of earthquakes were considered. In general, the soil in this area was found to be extremely variable. At worst, in parts of Brooklyn, very loosely compacted sand was encountered. This is susceptible to liquefaction causing major damage in even mild earthquakes. Analysis was conducted on representative structures. The results showed that for earthquakes in the higher end of the expected range, some structural failures can be anticipated as a result of insufficient allowances made at the time of design.

7. ECONOMIC CONSIDERATIONS

Having discussed the approach to earthquake-resistant design, and the technical provisions which promote safety to the structures, the subsequent question is: How much will provisions cost? This question is not easy to answer, and there does not appear to be one universal answer which applies to all situations. However, some general observations can be made.

In general, the cost of a structure is related to the amount of material used to construct it. For conventional loads, the dimensions of the structure are proportioned relative to that load. Thus, the amount of material and the cost of the structure are generally related to the magnitude of the loads. It is difficult, however, to clearly specify the individual costs contributed by each load because design is based on the controlling combination of loads.

In the case of earthquake provisions, it is even more difficult to generalize regarding the specific contribution to the cost of a structure. The earthquake loading may or may not govern the design. In California, it may be expected that the specific choice of structural details is controlled by seismic considerations. In other areas this may not be the case. Further, as has been discussed in the preceding sections, an earthquake does not simply contribute a load to the structure (like live or wind load) but it makes a demand for displacement requiring flexibility and ductility rather than strength. Indeed, increasing the size and thus the rigidity of structural members can increase the amount of the earthquake load they attract and make them less able to meet the displacement demands. This fundamental difference is important in defining costs associated with seismic provisions. Also, just as there are differences in the state-of-the-art treatment of aboveground and underground structures, it is expected that the seismic ramifications of cost will differ for each.

Although there are no formal guidelines that specify seismic considerations for underground structures, we have seen that the common approach is to allow the structure to conform to the movement of the surrounding earth while remaining stable against collapse. In general, the cost of seismic provisions is associated with the additional reinforcement used in making joints suitably ductile. Typically this might mean additional secondary reinforcement to confine the concrete and to contain the main reinforcement. There may be limitations on the number or location of reinforcement splices, and in general there may be more steel for a given volume of concrete. The additional amount of steel, and possibly the greater difficulty factor associated with placing it at a greater density, can lead to tangible cost increases. But how significant is this with regard to the entire cost of the structure? It is not likely in the case of a modern tunnel design, that the provisions for earthquakes would lead to a more stout structure requiring more cubic yards of concrete. In the case of a recent metro design in California, it was determined that the cost directly attributable to seismic factors was approximately a 5% increase in the reinforcement cost. To put this figure in perspective, it is necessary to consider the whole project cost.

As a hypothetical example, consider a cut-and-cover tunnel project with the costs shown in Table 7-1.

TABLE 7-1

Cut and Cover Tunnel Costs

Item	Cost
Mobilization	\$2,000,000
Earthwork	\$1,400,000
Foundation Drain	\$200,000

Reinforced Concrete	$25,000,000
Mechanical	$4,400,000
Ventilation	$3,000,000
Electrical	$5,000,000
Total	$41,000,000

For this example, concrete makes up 61% of the cost of the project. Assuming a unit cost for in-place concrete of $160 per cubic yard (not including reinforcing) and an average of 180 lb of reinforcing steel per cubic yard at $0.5 per lb, the reinforcing steel would make up 36% of the cost of the concrete, and 22% of the cost of the total project. Therefore, if the seismic considerations added 5% to the cost of the reinforcing steel, they would actually be adding 5% to the above 22%, i.e., they would add 1.1% to the cost of the project. If the above were a transit tunnel, and the actual transportation systems were to be added to the project cost (e.g., the cost of the trains and the power and control equipment) the impact of seismic considerations would be even smaller.

For abovegrade structures, specifically elevated guideway structures, the cost considerations are a little different. For these structures, the typical seismic provisions may be a combination of the following.

The girders are usually not impacted significantly by seismic considerations although the connections of the superstructure to the supporting pier/columns require additional provisions. This possibly leads to more confinement reinforcing, physical restrainers to prevent separation at expansion joints, and perhaps more elaborate bearings including isolation and energy dissipation details.

The columns usually experience the greatest amount of attention with regard to seismic considerations. It is not expected that the size of the columns would be increased for earthquake loads, because this would simply attract larger forces to them. The columns would, however, be designed to be more ductile, that is more capable of accommodating plastic deformations without losing their load-carrying capacity. This usually means that more steel reinforcement would be included to the columns without increasing their size. As in the case of a tunnel, the amount of concrete used might not increase but each cubic yard of concrete might contain a higher percentage of reinforcing steel.

In the area where the plastic hinges are expected to form, secondary reinforcement is particularly important in "holding the structural elements together" as they deform beyond their normal levels. Additionally, there may be a need for longer dowel bars connecting the column with the foundation and with the superstructure, and there may be a need to avoid splices in the reinforcement within certain areas of the column. The result is a greater amount of steel, and possibly a greater unit cost of the steel because of additional difficulty in placing it at higher densities.

The foundations are impacted by seismic considerations in a different way. According to the philosophy used for the design of elevated structures, the damage in an earthquake should be noncatastrophic (not causing collapse) and should be detectable and repairable. Logically, damage to the foundations should be avoided as this would be neither easily detectable nor repairable. The design approach in designing foundations is that they should remain elastic even when subjected to the ultimate forces transmitted from the columns. Therefore, even though the columns may not increase in size due to earthquake considerations, the foundations to which they are connected may have to be larger. Typical foundations for elevated guideway structures are pile caps and a number of driven or bored piles. Unlike the columns, the foundation costs might increase due to the additional volume of concrete necessary to provide earthquake resisting capacity.

In summary, for typical elevated guideway structures, the impact of seismic considerations might be additional detailing of the superstructure-to-substructure connections, additional "ductility" reinforcement in the columns, and a greater size of the foundations. According to the combined experience of several engineers who have designed elevated structures in seismically active areas, this might result in an increase between 10% and 20% in the structural costs. Because the structural costs are only one component of the total project cost, the overall percentage increase is smaller.

It should be remembered that the above estimate is for structures in seismically active areas where the design guidelines require a greater number of provisions. In seismically inactive areas the impacts would be considerably smaller.

In considering the cost of making a structure safe against earthquakes, is it correct to ask whether or not we can afford it? A more relevant question may be: Can we afford not to make the appropriate provisions? A brief review of damage and loss of life associated with the world's great historical earthquakes clearly indicates the high cost associated with the failures of inadequately constructed facilities, both private/domestic and large public facilities. Recent events in our own country, including San Fernando 1971 and Loma Prieta 1989, are good examples of private and public costs associated with earthquake damage. In such examples, the post-event analyses often concluded that much of the damage is to older facilities that were constructed without adequate seismic provisions. Had there been a greater awareness of seismic risk at the time of construction, many more structures might have survived with minimal additional investment.

The cost of replacing a collapsed structure, or one deemed unsafe, is obviously very high, both in terms of capital expenditure and in the social inconvenience suffered by the community during the interim period. Also, after the San Fernando earthquake motivated an extensive retrofitting program in California, it has been found that there are only limited seismic improvements which are practical to install after-the-fact.

In conclusion, it appears that adequate provisions at the time of construction can be made with modest increases in total investment. This is the case in seismically active areas, so the incremental costs would be even less in areas of low seismic risk. Also, the financial and social cost of major repair or replacement are not viable. Retrofitting is expensive, and the actual benefits are often of limited effectiveness. It is therefore apparent that the minor additional cost of building a safer structure is well justified.

8. DESIGN RECOMMENDATIONS FOR MASS TRANSIT FACILITIES

8.1 General

At the present time, the approach to earthquake design in this country is not uniform. Even allowing for the different levels of risk in different geographical areas, the methods used to design for the possibility of seismic activity vary according to the policies of the sponsoring agency, the judgment of the designer, and the requirements of local authorities. Additionally, different approaches are typically taken for different categories of structures, and although there are codes and guidelines covering many applications, it is not always clear which should be used for a specific project.

Many large projects, such as major transit projects, develop their own criteria. These criteria often incorporate many of the features of the available local and national codes supplemented by project-specific requirements. Supplementary requirements are usually based on the nature of the local geology, the type of facilities, and the acceptable levels of risk.

It is true that an earthquake's strength and characteristics depend greatly on the location, regional geology, and site conditions. It is also accepted that different types of structures will require different technical approaches. Nonetheless it would be desirable to have a nationally adopted design guideline which would allow the project to be responsive to its specific needs, while still ensuring that a minimum level of attention is paid to the problem of earthquakes. Such a guideline could consider all of the factors in the current codes, such as regional seismicity, categories of structure, and levels of risk, consolidating them for ease of use and clarity of application. It is important to recognize that any guideline should represent minimum levels of attention, and should not preclude project-specific enhancements made on the basis of special studies.

A uniform national document to guide the seismic approach for all projects may not be available for some time. At present, much of the onus is placed on the sponsoring agency to set the minimum standards for a project. For areas known to be seismically active, this often results in the use of several codes as well as supplementary site-specific requirements. In areas classified as having low seismic activity, earthquake considerations may be overlooked entirely. In the latter case, a false sense of security may result in designs with insufficient capacity to perform safely in the case of an earthquake.

Some of the more recent earthquake design technology is not yet incorporated into formal codes of practice, but is nevertheless used by designers. Often designers go beyond the requirements of existing codes because of the importance of maintaining lifelines in the event of a major quake. With some of the new approaches utilizing ductility rather than strength to derive safe performance, earthquake considerations can be included in construction with a relatively modest cost. Many of the features deemed desirable in surviving earthquakes, such as well-designed details, ductility, and security against collapse, represent good design practice even for conventional loads.

In the future, the federal government, specifically the public transit funding agencies, may require that a more formal approach to earthquake design be taken on all projects receiving federal funds. At that time it would be especially convenient to have a single set of national guidelines to use in design. For the present, we must use the documents and guidelines that are currently available, and to apply them correctly.

8.2 A Recommended Approach for the Implementation of Seismic Considerations.

Key factors to consider include type of earthquake, type of structure, and the acceptable levels of risk. The likely magnitude of an earthquake and average bedrock accelerations within a given region can be determined using the seismic zone maps as a guide. For areas where seismic activity is great, and especially for important projects, more detailed and specific information regarding the probable peak acceleration, risk of liquefaction, and permanent displacements across faults, should be determined. This is done by surveying the geology of the site and the region, investigating the nature of the soil and the depth of bedrock, and conducting a seismic study to estimate the probable characteristics of a nearby earthquake.

If the soil is susceptible to liquefaction or if an active fault zone is crossed, consideration should be given to changing the site. If these problems are unavoidable, much more extensive study may be required to arrive at an adequate design solution. The seismic study should determine the probable peak ground acceleration for two levels of earthquake: an Operating Design Earthquake (ODE), and a Maximum Design Earthquake (MDE). The ODE should have a return period of a few hundred years, with a relatively high probability that it would occur at least once during the life of the structure. For this event, a structure would be expected to sustain minimal damage and be able to continue to serve its function with minimal interruption. An MDE should have a return period of a few thousand years, with only a small probability of occurring during the service life of the structure. In this event, the structure would be expected to sustain limited damage.

With the current state of codes and standards, there is good documentation dealing with the design of highway bridges, which can be readily applied to typical elevated transit guideway structures. Similarly, buildings and the contents thereof are covered by separate codes. In the case of tunnels and underground structures, however, there is no officially accepted code to guide designers. With underground structures more than the other categories, the state of the art is still developing and is mainly in the hands of the practicing engineers.

The following summarizes the recommended general approach for the seismic design of elevated structures, underground structures, and maintenance facilities. Where the approach is already covered by design codes, the details are not repeated here.

8.2.1 Elevated Structures

For the purpose of this description, an elevated structure is defined as a girder-mounted guideway supported by a substructure of pier caps, columns, and foundations. Examples of this type of structure are fairly similar for transit projects around the world. Special structures such as cable-supported or long-span bridges are more unusual and may require special studies. These are not covered in this discussion.

For elevated structures, the best approach is that prescribed in the AASHTO Standard Specification for Highway Bridges. This adopts the philosophy of designing the structure to meet the displacement demands rather than expecting the structure to resist the peak forces.

In general, the approach taken should be as follows: The acceleration and motion characteristics of the Operating Design Earthquake (ODE) and the Maximum Design Earthquake (MDE) should be established and used as inputs to a dynamic analysis using an elastic (nonyielding) model of the structure. The peak forces determined by this analysis are those that would be generated by the earthquake if the structure could remain perfectly elastic. These fictitious forces are typically very high, and in the case of the MDE may be well beyond the limit of practical design.

How the elastic forces are used in design is different for the ODE and the MDE. By its definition, it is reasonable to assume that an ODE will be experienced during the life of a structure. It is obviously desirable that the resulting damage be minimal. Under such an event, a structure should not yield. For this reason, the structure is designed to remain elastic under ODE loads just as it is in the case of the conventional loading. For this event a certain amount of overstress is allowed, recognizing that it is unlikely that the earthquake would occur simultaneously with the maximum application of the other loads.

Damage is acceptable with an MDE provided it does not lead to catastrophic collapse and that the damage is detectable and repairable. For the MDE, the forces calculated in the dynamic elastic analysis are divided by a reduction factor which may vary between 2 and 6, or may be even higher. The structure is designed to remain elastic under the factored loads. Therefore, if the MDE occurs, the structural members will yield and suffer plastic displacement. The expected amount of displacement is reflected by the force reduction factor (sometimes called the ductility factor). A lower factor means that the plastic deformation will be less. A higher factor (and therefore, a lower design force) means that greater plastic displacements result, and the structure can have less strength but must have greater ductility. In general, the smaller the factor, the less is the level of damage expected during a Maximum Design Earthquake. The choice of reduction factor is made according to the policy of a particular project. A good example is the design of the BART extensions, where the low factor of 2 is used as a way to minimize the likely damage, and to facilitate the continuity of service during and immediately after a major earthquake.

Achieving the above concepts has certain ramifications in design and construction. The areas of a structure often susceptible to damage during overload are the joints. Special attention must be paid to the detailing of these. This may include more reinforcement, longer dowels, and a greater degree of concrete confinement. In the area where the plastic deformation is expected, it is particularly important to design the details such that the member is capable of achieving the plastic deformation without losing its load-carrying capacity. This is in essence the definition of ductility.

In the proportioning of sizes of structural members, a good design will force the plastic deformations to occur where they are easier to detect and repair. This is typically at the tops and bottoms of columns. The girders and foundations are designed so as not to yield under the forces transferred from the columns. The AASHTO and related documents make specific recommendations about detailing.

8.2.2 Underground Structures

Unlike bridges and elevated structures, there are no official codes or guidelines covering the design of underground facilities. In recent years, however, an approach has been used which, like that of elevated structures, concentrates more on displacement demand and ductility than on structural strength and stiffness. This approach was proposed by Kuesel in a 1969 paper during the time of the original BART design, and has been used on several transit projects since.

The premise is that the underground structure, because it is totally surrounded by earth, will conform to the deformations of the earth, especially if the structural stiffness is small relative to that of the earth. This assumption is reasonable for most competent soils and for rock. In the case of very soft soils, however, it is expected that the structural stiffness may not be negligible relative to that of the earth, and that the structure will locally influence the soil deformations. The resulting deformations will be less than free-field and must be determined by analysis which incorporates the soil/structure interaction. This refinement to the analysis is still under development. The approach is referred to as the "displacement" method.

The other, more traditional way to account for seismic impacts on an underground structure, is to expose it to incremental dynamic earth pressures. Even this approach is difficult because of the limited ability to correctly model the dynamic pressures. One method which has been used involves the Mononobe - Okabe method, which has been extensively used in Japan. This technique, however, is known to have limitations and can result in unconservative design. This approach can be referred to as the "pressure" method.

If the model used for analysis were perfect, the displacement approach and the pressure approach would achieve the same result. Since this is not the case, it is advisable to design the structure checking both methods. It should be noted that two are not additive, and the design should be based on the worse or controlling case.

The methodology for underground structure design should be as follows:

a. Determine the free-field soil deformation. Generally a simple computer program (such as Shake) can be used to compute the ground shear deformation as a function of the depth of soil. A design earthquake acceleration time history is inputed from the bottom boundary (e.g. bedrock).

b. Based on the tunnel's location, determine the differential free-field deformation between the top and the bottom of the tunnel.

c. With the given structure geometry and properties, apply a horizontal load such that the structure distorts laterally with that magnitude. Internal forces in the structural members are then obtained.

d. The resulting internal forces from step c are added to those obtained from static design.

e. The combined internal forces are checked against the maximum allowable. For the case of the Ordinary Design Earthquake, an overstressing of 50% may be allowable. For the Maximum Design Earthquake, the structure may be allowed to go the yield point provided potential mechanisms are avoided.

Based on the type of soil and the judgment of the designer, the analysis may have to be modified to account for the stiffness of the structure and the influence it may have on free-field soil deformations. Guidelines regarding the allowance for this soil/structure interface are currently under development.

8.2.3 Maintenance Facilities

The third major category of transit facilities is that including maintenance and storage facilities, miscellaneous utility buildings, and at-grade stations. These are typically low level (one-or two-story) buildings that may include storage yards, and probably include utilities, machinery, and equipment. Such buildings might be occupied regularly or only for infrequent maintenance activities. Typically, these operations are critical to transit service.

These facilities are best covered by the seismic provisions in the Uniform Building Code (UBC) 1991, which has been specifically developed for conventional buildings and their contents. Structures of this type are less likely to collapse during an earthquake than they are to suffer local damage to windows and architectural finishes. Additionally, supports for heavy machinery or utilities may fail in an earthquake, resulting in subsequent problems.

Failure of utility lines, such as gas or electricity services, can result in fire. The way in which utilities are brought into the building and supported within the building should be designed with considerations to the forces and movements that may occur during an earthquake. Where utility lines pass from one medium to another, for example, the transition between buried-in-ground, and cast-in-slab, support details should permit the relative movement which is likely to occur between the two areas. Where utilities are suspended from the structure (e.g., hang from the ceiling), the supports must either hold the line rigidly to the structure, or allow it to safely sway independently while still remaining attached. The latter approach is something used for fuel or water pipes.

Heavy equipment and machinery is common in maintenance facilities. This may include electrical transformers, bus washing equipment, or machines to maintain the wheels of rail vehicles. The supports must be designed to keep the equipment stable and in place. For heavy items, the horizontal forces generated in an earthquake can be considerable.

The UBC covers the seismic design of buildings and their contents. For a particular seismic zone and occupancy category, UBC gives the guidelines for designing seismic provisions. For these types of structures, special considerations must be given to the structural and architectural detailing. It is here that failure is most probable. This includes the support of suspended ceilings and fixtures, and the design of windows, partitions, and mezzanines. In applying the UBC, however, the choice of occupancy category should be carefully considered. Greater safety and security will result from adopting a special occupancy category rather than a standard occupancy category.

In addition to structural considerations, the preparation for earthquakes should include safety plans for contingency operations and procedures. These may include generating emergency power, switching off utility services, evacuation of patrons from incapacitated vehicles, and conducting safety checks prior to resuming service. Such plans will require training of personnel but can be implemented with minimal investment and may have great benefits during the confusion of a large earthquake.

APPENDIX A

Loma Prieta Earthquake - October 17, 1989

This recent occurrence of a significant earthquake within a North American urban environment, is a good source of information for future seismic planning. The Earthquake Engineering Research Institute (EERI) initiated a comprehensive survey of the effects immediately after the event. The findings are documented in EERI's Preliminary Reconnaissance Paper (reference No. 13), and some highlights are summarized below.

The earthquake's epicenter was located 10 miles north of the town of Santa Cruz near Monterey Bay, some 40 miles south of San Francisco. The average assigned magnitude was 7.1 on the Richter Scale, and the influences were particularly wide, extending north to Sonoma and east to Sacramento. The duration was only 10 to 15 seconds but the shaking was quite severe with ground accelerations of 0.67g near the epicenter and 0.25g in Oakland. The death toll of 67 was relatively light for an event of this magnitude, but the damage was extensive, estimated at $5.6 billion, and the number of people left homeless was about 10,000.

Local emergency services were able to cope with the problems although with some difficulties resulting from disruption to highway communications and utility failures. Fires were one of the biggest indirect problems resulting from the earthquake. Many were serious structural fires and some were the direct result of breaks in gas lines.

The origin of the earthquake was a relatively deep 18 kilometers below the surface. The source of the quake was on a section of the San Andreas Fault that had been previously identified as having a high probability of seismic activity. The nature of the subsurface soils is believed to have contributed considerably to the severity and the extent of the damage. The predominant phenomena included liquefaction, landslides, and the amplification of ground motions in the area's soft soils.

Liquefaction was largely responsible for the damage to private housing in the Marina District of the city. This area had the most dramatic impacts from both the shaking and the subsequent fires, and was particularly featured in the media coverage. Strong earth movements in the San Francisco area are largely attributable to the amplified ground movements within the deep layers of cohesive soil known as bay mud. In the Santa Cruz mountains, several hundred land slides caused damage to housing and disruptions to roads. Observed examples of geotechnical damage included pavement damage and roadway cracks, utility damage, tilting of houses, runway damage at Alameda and Oakland Airports, roadway slumps, and movement of retaining walls.

Most of the damage to buildings occurred in nonreinforced masonry buildings constructed prior to building codes. Many of the damaged buildings in San Francisco are in the downtown South of Market area where local soil conditions were particularly detrimental. Many buildings, although not appearing severely damaged were declared unsafe.

Damage to engineered buildings was moderate, there were examples of minor damage to steel buildings, loss of brickwork on steel-framed brick buildings, damage to structures under construction, building-to-building pounding, loss of surface precast panels, and even damage to suspended ceilings at the San Francisco Airport. In general, the newer structures performed well and the overall objective of preventing catastrophic collapse was achieved.

One of the major effects of an earthquake or any natural disaster, can be the impact on lifelines, including transportation, water supply and sanitary drainage, power and gas distribution, and communications. This phenomenon and its effect on the community has been one of the major characteristics of the Loma Prieta earthquake.

The highway system suffered the worst damage, with the collapse of over one mile of the elevated roadway on I-880 through Oakland (The Cypress Street Viaduct). This was a particularly catastrophic failure where the upper level of the two-level roadway collapsed onto the lower. This structure failure was the major contributor to the death toll. Additionally, a 50 ft. span was lost on the upper deck of the Bay Bridge which provides the primary vehicular link between San Francisco and Oakland. Of the 1500 highway bridges in the area, three had span collapses, 10 were closed due to damage, 10 required shoring to maintain safety, and about 20 suffered minor damage. The greatest damage was to older structures. After the 1971 San Fernando quake, the codes were revised and a retrofit program was initiated, and therefore many structures were better able to survive. It is speculated, however, that if the duration of the shaking had been longer, more of the older structures similar to the Cypress Viaduct, might have been severely damaged.

Figure A-1 Collapsed Upper Deck of I-880 Cypress Structure

There were other problems related to transportation in the area. The main highway connecting Santa Cruz and San Jose was disrupted by a landslide. Damage to the control tower at the San Francisco Airport closed operations for 13 hours. There was also damage to the road-bed for the Caltrain commuter train connecting San Francisco and San Jose. The BART system was undamaged, however, and service was interrupted for only a few hours, just long enough to conduct a safety check of the system.

There was damage to the water distribution system in the form of leaks due to ground deformations. Drops in the water pressure added to the difficulty of fighting fires. In fact, a fire boat was called into service to aid in the supply of water at adequate pressure. Some sewage lines also failed.

There was a loss of power to about 1.4 million customers. Most of the power was restored within 48 hours. Damage was also sustained by gas transmission lines. The loss of service to customers caused a particularly high service load because gas company personnel typically are involved in the relighting of pilot lights.

The telephone system was subject to only minor damage. The main impact on service was due to the demand overload following the earthquake.

Overall the level of damage to infrastructure varied greatly. One very reassuring result, however, was the performance of the public transit facilities. This is largely attributable to the attention paid to seismic considerations by the transit agencies during the planning of their facilities. This success should be taken with caution, however, as the Loma Prieta quake was of relatively short duration.

APPENDIX B

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